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Using Stochastic Dynamic Programming to Support Water Resources Management in the Ziya River Basin, China

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Abstract: Water scarcity and rapid economic growth have increased the pressure on water resources and environment in Northern China, causing decreased groundwater tables, ecosystem degradation, and direct economic losses due to insufficient water supply. The authors applied the water value method, a variant of stochastic dynamic programming, to optimize water resources management in the Ziya River basin. Natural runoff from the upper basin was estimated with a rainfall-runoff model autocalibrated using in situ measured discharge. The runoff serial correlation was described by a Markov chain and used as input for the optimization model. This model was used to assess the economic impacts of ecosystem minimum flow constraints, limited groundwater pumping, and the middle route of the South–North Water Transfer Project (SNWTP). A regional climate shift has exacerbated water scarcity and increased water values, resulting in stricter water management. The results show that the SNWTP reduces the impacts of water scarcity and impacts optimal water management in the basin. The presented modeling framework provides an objective basis for the development of tools to avoid overpumping groundwater resources at minimum costs. **DOI:** **10.1061/(ASCE)WR.1943-5452.0000482.** *This work is made available under the terms of the Creative Commons Attribution 4.0 International license, http://creativecommons.org/licenses/by/4.0/.*

Author keywords: Water resources management; China; Water shortage; River basins; Optimization models; Economic analysis; Stochastic models; Reservoir operation.

Introduction

Population growth and rapid development of the Chinese economy have placed water resources and water quality in Northern China under increasing pressure in recent decades (Liu and Xia 2004). In the North China Plain (NCP), water resources are vulnerable; recent expansions of irrigation agriculture, in combination with climatic variability, have intensified the need for water in the area (Liu et al. 2001; Liu and Xia 2004; Mo et al. 2009). Rapidly decreasing groundwater tables, dry rivers, and heavily polluted surface water bodies represent consequences of the human development in the area (Liu and Xia 2004; Mo et al. 2009; Zheng et al. 2010). Increasing focus on ecosystem protection, sustainable groundwater pumping, and economic impacts of water scarcity complicate the decision making for water resources management in Northern China. To reduce the impacts of water scarcity, China has invested in the South-to-North Water Transfer Project (SNWTP), which will transport water from the south to the dry north (Yang and Zehnder 2005; Feng et al. 2007).

Reservoir management in water-scarce environments with significant hydrologic uncertainty, such as the NCP, is challenging; suboptimal management can lead to economic losses for water users during droughts or to water spills during floods. Therefore, many robust, unbiased, and rational tools for supporting water allocation decisions have been reported in the literature during the last decades; Harou et al. (2009) provided a good overview. River basins often represent highly coupled management problems with different water sources, a mix of conflicting water users, and multiple reservoirs. Whereas simulation models can address a high level of detail, optimization approaches have traditionally been kept simpler owing to difficulties in mathematically expressing the complexity of the decision problem and in maintaining a computationally feasible optimization problem (Loucks and van Beek 2005; Harou et al. 2009). The hydropower sector has historically faced similar optimization problems while trying to predict the management of reservoir systems, yielding, for example, the highest hydropower benefits (Pereira and Pinto 1991; Wolfgang et al. 2009). The water value method, which is based on stochastic dynamic programming (SDP), is a widely used technique to optimize reservoir operation (Stage and Larsson 1961; Stedinger et al. 1984;

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Pereira and Pinto 1991). This paper presents a more general application of the water value method in water resources economics and integrated water resources management.

This study demonstrates a method to support the optimal management of scarce water resources at the basin scale. A rainfall-runoff model is used to estimate natural surface water availability for water users situated upstream a reservoir. The optimal water allocation problem is formulated as a cost minimization problem subject to a demand fulfillment constraint. The water users are characterized by water demands to be satisfied by different water sources at different costs. Each user is also characterized by a cost of curtailment, and optimal management is defined as the reservoir operation that minimizes the total costs over the planning period. The water value method is applied in a general hydroeconomic context to optimize reservoir operation in the Ziya River basin on the NCP and is used to assess the potential benefit of the middle route of the SNWTP.

The current approach is demonstrated on the Ziya River basin, a separate subbasin in the highly exploited Hai River system, to illustrate the complexity of the decision problems faced by water managers during extreme water scarcity and to highlight the impacts of the SNWTP on optimal reservoir management. The basin is located southwest of Beijing in semiarid/semihumid Northern China (Fig. 1) and includes a downstream area located on the NCP. The precipitation (annual average of 500 mm) is highly seasonal, with 70% falling in the summer, and large interannual variations from 300 mm/year in dry years to more than 900 mm in wet years (China Meteorological Administration 2009). Therefore, the intensively irrigated spring wheat of the wheat-maize double cropping system in the downstream basin is highly dependent on irrigation water availability (Sun et al. 2010). Runoff can be stored in multiple reservoirs upstream the NCP and released when needed. However, the uncertain reservoir inflows and high water demands complicate reservoir management and increase the risk of economic losses attributable to water scarcity. The problem becomes more complex with the two-stage implementation of the middle route of the SNWTP. Since 2008, water from Shijiazhuang to Beijing has been transferred along the middle route ("SNWTP, pre-2014" in Fig. 1) (Water-Technology.Net 2013). From 2014 onward, water will flow from the Yangtze River in the south to the NCP and Beijing ("SNWTP, post-2014" in Fig. 1). Further, the decision makers have introduced minimum annual flow requirements to the Baiyangdian Lake, which decreases the amount of water available for irrigation.

Optimization Model Setup

The optimal reservoir operation rules for the multiple major reservoirs of the Ziya River basin were found by using an SDP approach (as discussed in a later section). Including all five major reservoirs (Huangbizhuang and Gangnan reservoirs on the Hutuo River northwest of Shijiazhuang and Lincheng, Zhuzhuang, and Dongwushi reservoirs south of Shijiazhuang) as separate states into the model would make the model computationally intractable owing to the well-known curse of dimensionality. Therefore, the reservoirs were aggregated, assuming that the releases from all reservoirs can be diverted to any point in the downstream basin. This assumption is realistic because the primary rivers of the downstream basin

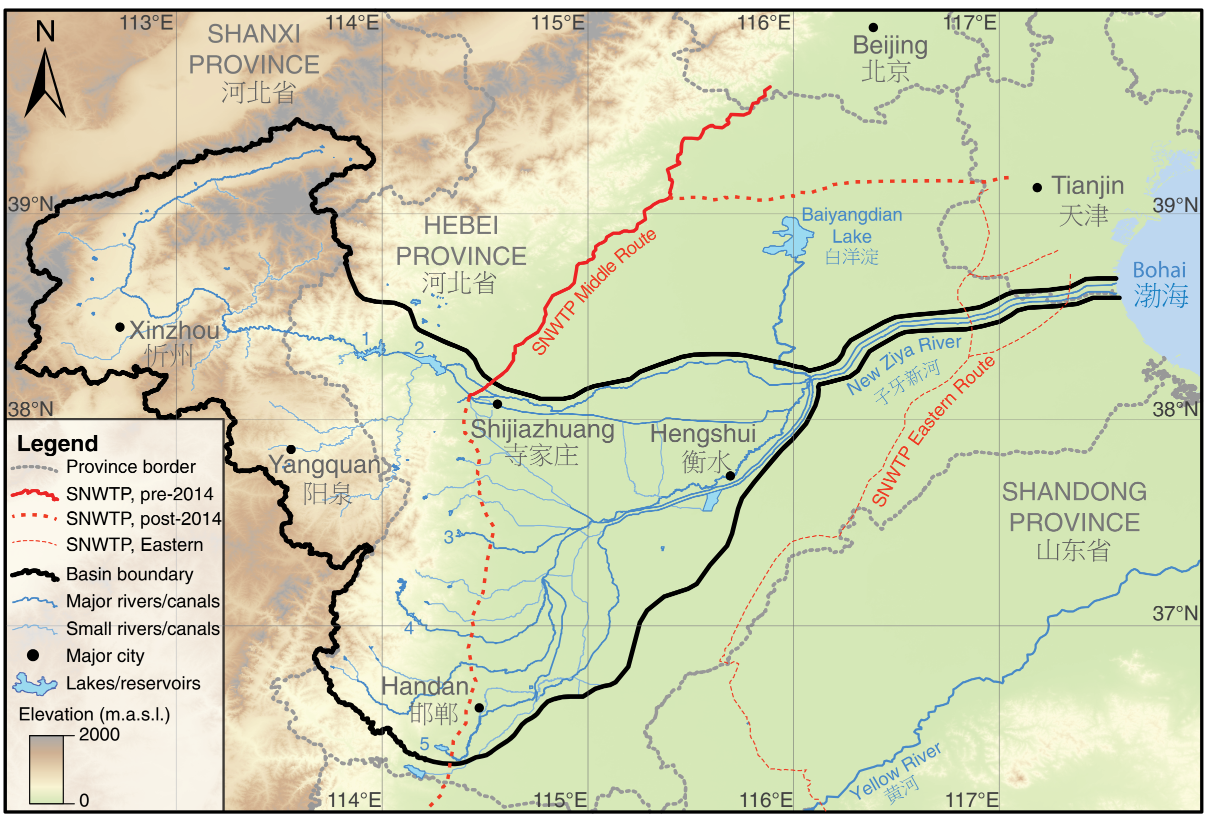

Fig. 1. Ziya River basin including main rivers, reservoirs, primary cities, and SNWTP routes; the major reservoirs are numbered: Gangnan (1), Huangbizhuang (2), Lincheng (3), Zhuzhuang (4), and Dongwushi (5) [the rivers and canals were automatically delineated from the Shuttle Radar Topography Map digital elevation map (Rabus et al. 2003) and manually verified and corrected by using Google Earth and the cover map in Ministry of Water Resources (MWR) Bureau of Hydrology (2011); the SNWTP routes were sketched in Google Earth and partly adapted from field observations and a map by Daxixianpipi (2011); and the provincial boundaries were downloaded from the National Geomatics Center of China (NGCC 2009)]

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are strongly linked with smaller canals. Conceptually, this single reservoir receives the combined runoff from the basin situated upstream the reservoirs. The water users of the upstream basin were divided into three groups; agricultural maize production, industry, and domestic. The water demand of these users can be satisfied with either river runoff or groundwater (no surface water storage).

Unused upstream runoff flows to the aggregated reservoir, where it is stored for the downstream water users, which are grouped into agricultural wheat-maize production, domestic, and industry. Reservoir releases generate hydropower up to a turbine capacity, and basin outlets flow to the Baiyangdian Lake and to the Bohai Gulf. The downstream users also have access to groundwater and water from the middle route of the SNWTP. Water from the reservoir can be diverted into the canal and sent to the city of Beijing. This setup makes it possible to test the impact of the new canal on optimal management of the reservoir.

Rainfall-Runoff Model

The natural runoff to the reservoirs at the western boundary of the NCP was estimated from the seven subcatchments shown in Fig. 2. A simple conceptual water balance model based on the Budyko framework was used to simulate daily runoff (Zhang et al. 2008). The Hargreaves method was used to estimate daily evapotranspiration from daily maximum and minimum temperatures. The simple model is based on Budyko's assumption that rainfall and available energy determine the long-term annual evapotranspiration from a catchment (Budyko 1958; Zhang et al. 2008). Budyko derived a water balance model (the Budyko curve) based on this assumption. This empirical relationship describes runoff as the fraction of precipitation not used to satisfy the evaporative demand (Zhang et al. 2008; Roderick and Farquhar 2011). Zhang et al. (2008) applied the Budyko framework for shorter time steps and allowed for water storage between time steps. A set of calibration parameters, including evapotranspiration efficiency and groundwater storage, controls the resulting discharge (Zhang et al. 2008).

The Yehe River tributary of the Hutuo River in the Taihang Mountains (gray shaded in Fig. 2) was used as a calibration subcatchment, with in situ measured discharge from the Pingshan station (Number 30912428) [Ministry of Water Resources (MWR) Bureau of Hydrology 2011]. This catchment has a relatively low population density and small reservoirs, so the flow regime was assumed to be close to natural. The runoff from this catchment was autocalibrated with daily measured discharge from 1971–1980, 1983–1991, and 2006–2008 [Ministry of Water Resources (MWR) Bureau of Hydrology 2011] with the objective of maximizing the monthly Nash-Sutcliffe efficiency (NSE). The resulting calibration parameters were applied to the other six mountainous subcatchments. The calibrated rainfall-runoff model was forced with 51 years (1958–2008) of daily precipitation and maximum and minimum temperature measurements from six weather stations (China Meteorological Administration 2009). Spatial interpolation of weather station data was performed with Thiessen polygons.

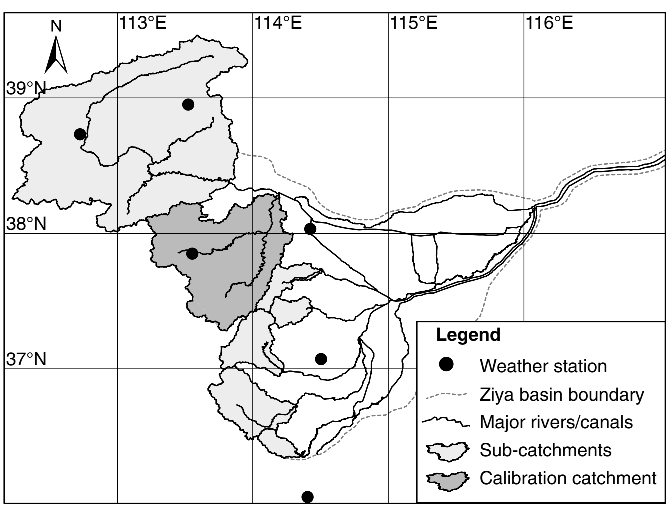

Fig. 2. Upstream subcatchments extracted from the digital elevation maps of Rabus et al. (2003) in the rainfall-runoff model and the weather stations from China Meteorological Administration (2009)

The combined simulated daily runoff from all upstream subcatchments (Fig. 2) was aggregated to monthly time steps and normalized. Each monthly discharge was assigned an inflow class [dry (0–20th percentile), normal (20th–80th percentile), or wet (80th–100th percentile)], and the transition probability matrix, $\mathbf{P}_{k,l}$, was determined by counting the number of transitions from each inflow class in month k to each inflow class in month l. This aggregated data set was used to represent the stochastic properties of the natural reservoir inflow, and hence, used as input to the optimization model. The Markov chain was validated to ensure second-order stationarity (Loucks and van Beek 2005). The Markov chain was used to generate a synthetic runoff time series, which was tested against the measured runoff for stationary mean and variance.

Stochastic Dynamic Programming and Decision Support

For a system with M users denoted with index m, the total costs, tc, of satisfying the demand of the users in each stage can be formulated as the cost, c, of allocating or curtailing (ct) the user x amounts of water

$$tc = \sum_{m=1}^{M} (c_{sw}x_{sw} + c_{gw}x_{gw} + c_{cn}x_{sn} + c_{ct}x_{ct})_m \tag{1}$$

In the Ziya River basin, the water sources are surface water (sw), groundwater (gw), and water from the SNWTP middle route (sn); the supply costs arise from pumping, treatment, and conveyance. Alternatively, the users can be curtailed, which leads to curtailment costs (as discussed in a later section). Although surface water is often associated with the lowest direct cost to the users, the absence of surface water will force the users to switch to curtailment or alternative, more expensive, sources. With scarce surface water resources and limited storage capacity combined with large seasonal and annual precipitation variations, present releases will decrease future surface water availability. Thus, present costs should be balanced against future uncertain costs. These costs are coupled in time because the reservoirs allow storage for future use (dynamic problem). Therefore, the one step ahead allocation problem for a given stage cannot be solved independently from the other stages. Incorporation of uncertain reservoir inflow adds stochasticity to the system.

The authors used SDP to develop rational reservoir operation rules in the uncertain environment, a method known in the hydropower sector as the water value method (Stage and Larsson 1961; Stedinger et al. 1984; Pereira et al. 1998; Loucks and van Beek 2005; Wolfgang et al. 2009). The backward recursive SDP equation runs in monthly time steps (stages) and calculates the minimum of the sum of immediate and expected future costs by using the classical Bellman formulation [Eq. (2)] for all discretized reservoir states (water levels). The objective is to minimize the total costs given by the optimal value function $F_t^*(V_t, Q_t^k)$ while satisfying water demands [Eqs. (3)–(7)]

$$F_t^*(V_t, Q_t^k) = \min\left\{\sum_{m=1}^{M}\sum_{n=1}^{N}(c_n x_n)_{m,t} - r_t b_{hp} + \sum_{l=1}^{L}[p_{kl}F_{t+1}^*(V_{t+1}, Q_{t+1}^l)]\right\} \quad (2)$$

where V_t = reservoir storage at stage t; n = sources shown in Eq. (1); p_{kl} = reservoir inflow serial correlation that describes the probability of a transition from a flow class k reservoir inflow, Q_t^k, in stage t to a flow class l reservoir inflow, Q_{t+1}^l, in stage $t+1$. Because the future cost function is convex, future costs can be constrained from below by a set of linear constraints derived from the discrete sampling of total costs, F_{t+1}^*, as described by Pereira and Pinto (1991). The optimal solution will have a future cost that falls on one of these linear constraints. The set of linear constraints on the future cost is integrated with the remainder of the optimization problem to form one single linear program for the one step ahead optimization problem [Eq. (8)]. Three flow classes were defined for every month, as described previously, owing to the length of the simulated runoff series. The benefits from hydropower production (reservoir releases r times marginal production benefit, b_{hp}) are subtracted from the immediate costs. The optimization problem is defined by the objective function [Eq. (2)] subject to constraints on water demand fulfillment [Eq. (3)], water balance of the reservoir [Eq. (4)], water balance of reservoir releases [Eq. (5)], upstream releases [Eq. (6)], and releases to Beijing [Eq. (7)]

$$sw_{m,t} + gw_{m,t} + sn_{m,t} + ct_{m,t} = d_{m,t} \quad (3)$$

$$V_t + Q_t - \sum_{u=1}^{U} sw_{u,t} = V_{t+1} + r_t + s_t \quad (4)$$

$$r_t + s_t = \sum_{d=1}^{D} sw_{d,t} + Q_{\mathrm{out},t} \quad (5)$$

$$\sum_{u=1}^{U} sw_{u,t} \le Q_t \quad (6)$$

$$sw_{\mathrm{Beijing},t} + sn_{\mathrm{Beijing},t} \le cp_{\mathrm{SNWTP}} \quad (7)$$

$$FC \ge \lambda_h(V_{\mathrm{end}} - V_h) + FC_h \quad (8)$$

where $sw_{m,t}$, $gw_{m,t}$, and $sn_{m,t}$ = surface water, groundwater, and SNWTP water allocations, respectively; $ct_{m,t}$ = water curtailment of user m in stage t; and $d_{m,t}$ = given demand of user m. The dynamics of the system is described by a water balance equation [Eq. (4)] linking reservoir storage in $t+1$ to reservoir storage in t, where $\Sigma sw_{u,t}$ is the sum of surface water allocations in stage t to the upstream user, u (U users). The total reservoir releases consist of release through the hydropower turbines, r_t, and spills, s_t, exceeding the turbine capacity. The combined reservoir releases $(r_t + s_t)$ must equal the combined surface water allocations to the D downstream users (denoted d) and unused outflow, Q_{out}, from the basin [Eq. (5)]. The upstream water users are constrained by the upstream runoff [Eq. (6)] and the combined allocations to the Beijing user (reservoir releases from Ziya River basin, $sw_{\mathrm{Beijing},t}$, and SNWTP water from Yangtze River, $sn_{\mathrm{Beijing},t}$) are constrained by the capacity of the middle route of the SNWTP, cp_{SNWTP} [Eq. (7)]. The piecewise linear future cost function, FC, was added as h linear pieces, as shown in Eq. (8), with slopes λ_h representing the shadow prices logged in $t+1$, h an index of the discrete reservoir storage levels, and FC_h the future costs logged in $t+1$. The linear problem optimizer *CPLEXLP* (IBM 2013) was chosen for its high efficiency.

The outcome of the optimization [Eq. (2)] is two (stages by states) matrices with minimum total costs (CNY) and shadow prices (CNY/m^3), with CNY representing 2005 Chinese yuan. As alternative to directly logging λ, the water values, θ(CNY/m^3), can also be found as the first derivative of the total costs with respect to the discretized reservoir volumes (Stage and Larsson 1961)

$$\theta = \frac{\partial F_t^*}{\partial V_{t+1}} \quad (9)$$

To avoid the effect of the end condition (future cost = 0), the model is run to equilibrium by looping the annual input data until the interannual differences in water values become insignificant. The initial year furthest from the end condition is used as the equilibrium water value table. The equilibrium water value tables, one for each inflow class, are used to guide a forward moving simulation phase similar to the optimization phase. From a given reservoir storage at time t, the water values are used as future costs to determine the allocation of water between current use and storage for the future. A perfect foresight dynamic program (DP) with a single future cost function (similar setup as the SDP optimizer) is used to evaluate the performance. With perfect foresight, this test will show exactly how well it is possible to manage the water resources; the test can be used to benchmark the performance of the SDP optimization.

Curtailment Costs and Water Demands

A central input for the optimal value function [Eq. (2)] is the curtailment cost of the water users. This cost describes the marginal cost in monetary units (CNY/m^3) for not satisfying a user's water demand. For agricultural users, the calculations were based on literature estimates of the crop water use efficiency, WUE (Table 1), in the lower part of the basin (Mo et al. 2009). The curtailment cost was estimated as

$$cc = \mathrm{WUE} \times p \quad (10)$$

where cc = curtailment cost of the crop and p = producer's price of the crop, scaled to 2005 prices by using the consumer price index (World DataBank 2013). The irrigation demands and schedule for the individual crops are based on field interviews from March 2013 of 22 farmers distributed within the Ziya River basin (Table 1) and fall in the same range as in the literature (Liu et al. 2001; Mo et al. 2009). The total irrigated areas were extracted as the land use classes "Dryland Cropland and Pasture" and "Irrigated Cropland and Pasture" in the USGS Euroasia Landcover Map (USGS 2013). These land use classes were evaluated as irrigated based on field observations.

Industrial water demands were estimated from Hai River statistics and scaled with the upstream and downstream areas (Berkoff 2003; Moiwo et al. 2009). The industrial curtailment costs were based on a previous study of the industrial water value in the Hai River basin (World Bank 2001) and not differentiated between upper and lower areas (Table 2).

Domestic demands were estimated from provincial per capita water consumption statistics, as listed in Table 2 [National Bureau of Statistics of China (NBSC) 2011]. The demands were scaled to the upper and lower basins with the 2007 Landscan population density map (Berkoff 2003; Bright et al. 2008). The curtailment costs were based on a previous study of the water scarcity damage costs for the domestic users in the Hai River basin (World Bank 2001).

Table 1. Model Input Data Including Water Demands, Water Values, and Reservoir Properties

Input data	Value	Unit	Source
Industrial water demands			
Hai River basin	6.6	km^3/year	Berkoff (2003)
Area of Hai River basin	318,866	km^2	Moiwo et al. (2009)
Area of Ziya River basin	52,299	km^2	
Area upstream reservoirs	26,048	km^2	
Total water demand[a]	1,083	mm^3/year	
Downstream demand[a]	543	mm^3/year	
Upstream demand[a]	539	mm^3/year	
Industrial water values (curtailment costs)			
Urban[b]	6.4	CNY/m^3	World Bank (2001)
Rural[b]	4.3	CNY/m^3	World Bank (2001)
Average	5.3	CNY/m^3	
Domestic water demands			
Hebei Province	123	L/person/day	NBSC (2011)
Shanxi Province	106	L/person/day	NBSC (2011)
Total population inside basin	25.0	Million people	Bright et al. (2008)
Upstream population	5.8	Million people	Bright et al. (2008)
Downstream demand	864	mm^3/year	
Upstream demand	223	mm^3/year	
Water demand in Beijing[c]	1,000	mm^3/year	Ivanova (2011)
Domestic water values (curtailment costs)			
Urban[b]	3.2	CNY/m^3	World Bank (2001)
Rural[b]	3.2	CNY/m^3	World Bank (2001)
Average	3.2	CNY/m^3	
Curtailment cost in Beijing[b]	5.5	CNY/m^3	Berkoff (2003)
SNWTP, middle route			
Inflow from Yangtze	9,500	mm^3/year	Water-Technology.Net (2013)
Water demand 100 cities	7,400	mm^3/year	Wang and Ma (1999)
Arable land on the NCP	179,500	km^2	Liu et al. (2011)
Water for NCP users in Ziya[d]	1,307	mm^3/year	
Ecosystem water demand			
Minimum diversion[e]	100	mm^3/year	
Reservoir storage			
Dongwushi	152	mm^3	Hai River Water Resources Commission (HWCC) (2012)
Gangnan	1,570	mm^3	HWCC (2012)
Huangbizhuang	1,210	mm^3	HWCC (2012)
Lincheng	180	mm^3	HWCC (2012)
Zhuzhuang	436	mm^3	HWCC (2012)
Aggregated reservoir storage	3,548	mm^3	
Hydropower production			
Maximum turbine capacity[f]	1,500	mm^3/month	Hebei Research Institute of Investigation and Design of Water Conservancy and Hydro-power (HEBWP) (2013)
Electricity price[b]	0.40	CNY/kWh	China Daily (2012)
Installed turbine capacity	69	MW	Aggregate[g]
Hydropower benefits[h]	0.036	CNY/m^3	

Note: All prices have been converted to 2005 CNY with the consumer price index based on World DataBank (2013).
[a]Demands scaled with the areas.
[b]Converted to 2005 prices.
[c]Based on plan described by People's Government of Hebei Province (2012).
[d]Remaining SNWTP water distributed evenly to NCP arable land and scaled to the downstream Ziya River basin.
[e]Estimated demand of Baiyangdian Lake based on Honge (2006). Model ecosystem diversions fixed to July.
[f]Capacities from Huangbizhuang, Zhuzhuang, and Dongwushi Reservoirs scaled to the remaining reservoirs.
[g]HEBWP (2013); HWCC (2013); Baidu Encyclopedia (2012, 2013a, b).
[h]Estimated from maximum production, maximum turbine capacity, and current electricity price.

The water demand and curtailment costs of the Beijing user were based on the same study.

The ecosystem water demands could have been included as regular water users in the optimization framework, but owing to a lack of ecosystem water values, ecosystem water requirements were added as demand constraints, based on an estimate of the deficit in the water balance of the Baiyangdian Lake, as listed in Table 2 (People's Government of Hebei Province 2012).

The supply costs of surface water and SNWTP water were set to zero. Benefits from hydropower production will favor surface water allocations over SNWTP allocations to the downstream users. A constant groundwater pumping price of 0.4CNY/m^3 was used, based on field interviews. This price represents only the electricity costs for pumping: pumping costs from irrigation canal to field were not included.

The SNWTP water available for allocation to the Ziya River basin was estimated from the data in Table 2. Different expected water transfer rates for the middle route are reported in the literature, including 5 km^3/year (Jia et al. 2012), 9 to 13 km^3/year (Berkoff 2003), and 9.5 km^3/year, as presented in Table 2

Table 2. Irrigation Schedule, Water Use Efficiencies, Producer Prices, and Water Values for Wheat and Corn Agriculture in Hebei and Shanxi Provinces

	Irrigation schedule[a] (mm)						Water use effeciency[b]	Producer prices[c]	Curtailment cost	Area[d]
Agricultural water user	March	April	May	June	July	Total	kg/mm/ha	CNY/kg	CNY/m^3	km^2
Shanxi, corn	50	50	—	50	50	200	16	1.62	2.6	2,846
Hebei, corn[e]	—	—	—	—	100	100	16	1.62	2.6	15,223
Hebei, wheat[e]	100	100	100	100	—	400	14	1.61	2.3	15,223

Note: All prices are in 2005 CNY, calculated with the consumer price index based on World DataBank (2013).
[a]Based on field interviews of 22 farmers within the basin.
[b]Estimated from Mo et al. (2009).
[c]USDA Foreign Agricultural Service (2012), converted from 2011.
[d]Based on land use classes "Dryland Cropland and Pasture" and "Irrigated Cropland and Pasture" in USGS (2013).
[e]Double cropping system so the same area is used for wheat in the spring and corn in the summer.

(Water-Technology.Net 2013). As a boundary condition for the model, the fraction of water available for allocation has been defined as 9.5 km^3/year minus 7.4 km^3/year for the 100 major cities in the north (Wang and Ma 1999). The remaining 2.1 km^3/year were distributed evenly to the arable land of the NCP and the share available to Ziya was found. The Beijing water deficit of 1 km^3/year (Ivanova 2011) was considered part of the 7.4 km^3/year value and added to the SNWTP water available in the model.

Monte Carlo simulations are used to assess the uncertainty of economic models. The input uncertainties were initially estimated and a set of samples were generated with Latin hypercube sampling (LHS). The water demands and curtailment costs were assumed to be normally distributed, with SDs of 20% around the estimated value. The hydropower benefits were assumed to be uniformly distributed with 80% uncertainty. Each uncertain input is examined once per sample. With 17 uncertain parameters (eight demands, eight curtailment costs, and hydropower benefits) a sample size of $n = 50$ was found to be sufficient. The n results were used to estimate SDs.

Results

Rainfall-Runoff Model

The rainfall-runoff model was autocalibrated to measured runoff in the calibration catchment shown in Fig. 2. Despite the absence of major reservoirs in the calibration catchment, the measured runoff included delayed peaks occurring in the dry winter months, as shown for the early years in Fig. 3. The authors expect these peaks to be a result of reservoir releases, because the timing fits the normal irrigation practices in the region. In certain later years, peak summer discharge is very low, despite the occurrence of precipitation events similar to the early period. The highest achievable monthly NSE for all of the 7,700 overlapping days is 0.47 (calibration target), which increases to 0.64 if the winter months are not used for calculation of the NSE. The water balance error, $(\mathrm{sim} - \mathrm{obs})/\mathrm{obs}$, is 10%. The calibration catchment contains multiple smaller reservoirs to serve irrigation agriculture and almost 2 million people. Therefore, the observed discharge may deviate significantly from discharge under natural conditions. Before using these presented results in actual decision making, the modeling framework should be updated with more realistic estimates of the natural water availability, preferably by using observed river discharge time series.

The assumption of stable conditions in the basin is a prerequisite for reaching steady-state water value tables. However, the simulated runoff shows a decreasing tendency over the 51 years. Plotting the accumulated mean precipitation for the three weather stations used for the Shanxi Province (Fig. 4) reveals that the precipitation has been decreasing over the period. This has previously been discussed in the literature (Chen 2010; Sun et al. 2010; Cao et al. 2013). Based on a simple manual fit, the simulation was split into two climate periods with a shift in 1980, in which each period is assumed to have stationary precipitation.

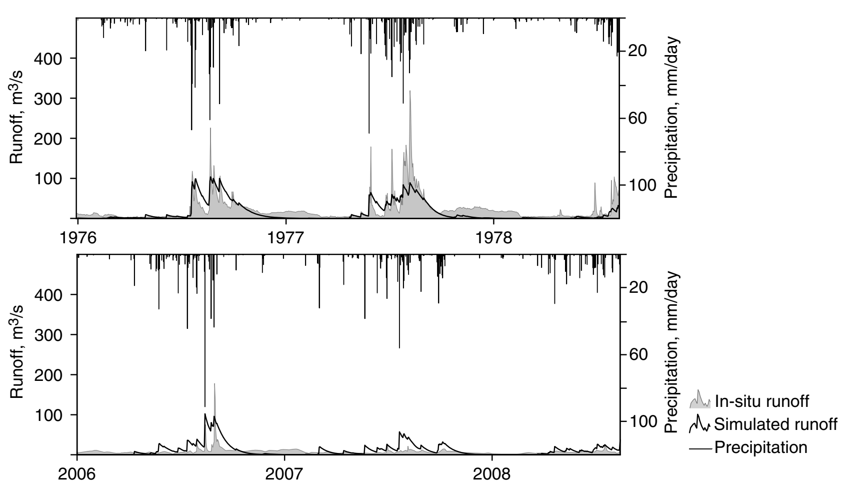

Fig. 3. Measured runoff, simulated runoff, and precipitation time series for two periods in the calibration catchment [data from China Meteorological Administration (2009) and Ministry of Water Resources (MWR) Bureau of Hydrology (2011)]

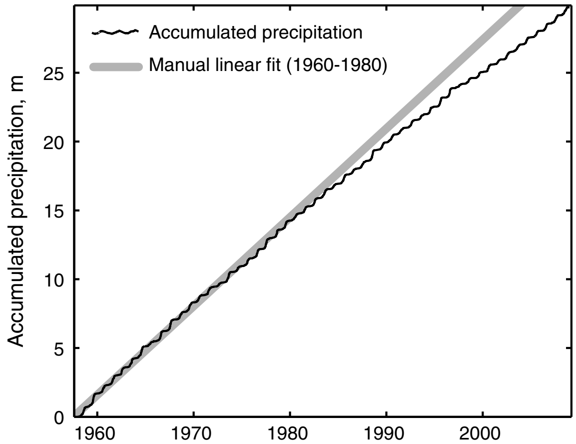

Fig. 4. Accumulated precipitation in the Shanxi Province with a manual linear fit to the first years (1958–1980): average of Stations 53673, 53588, and 53782 [data from China Meteorological Administration (2009)]

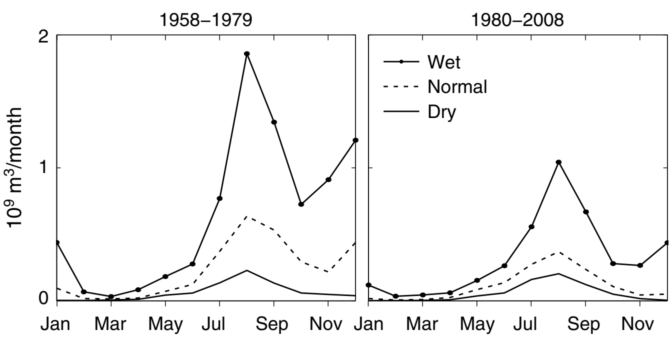

Fig. 5. Monthly discharge for the three flow classes during the two regional climate periods

The average flow of each inflow class is shown in Fig. 5. The timing of the peak flow is similar in the period 1980–2008, but the magnitude of the flow is lower. In particular, the dry winter months from November to February are drier in the period 1980–2008.

Stochastic Dynamic Programming

The backward recursive SDP algorithm [Eq. (2)] was run with a looped 10-year sequence of the annual input data to reach interannual equilibrium water value tables for each climate period. The resulting water value tables for three scenario runs are shown in Fig. 6. The water values are highest at low reservoir states and in the dry periods, with water values above $0.3\text{CNY}/\text{m}^3$. In wet months and at high reservoir states, the water value drops below $0.2\text{CNY}/\text{m}^3$. Comparing different inflow classes shows that a dry flow class results in higher water values (more conservative reservoir management) than in the normal or wet flow class. The lower reservoir inflow in the period 1980–2008 results in increased water values, and therefore, more conservative reservoir management with lower reservoir releases. The large blue areas with water values around $0.4\text{CNY}/\text{m}^3$ in the two scenarios with unlimited groundwater pumping are caused by the groundwater pumping price, which is lower than any of the users' curtailment costs. In the scenario with the partly finished middle route of the SNWTP, the Beijing user is constrained to surface and SNWTP water alone, because the groundwater in this area is already fully exploited. If no surface water is available, the user can only be curtailed. This increases the water value whenever the reservoir is close to empty, and the demand cannot be satisfied with the in-stage runoff alone. After the SNWTP middle route has been completed, the water diverted from the Yangtze River can completely satisfy the Beijing demand, so the water value at low states becomes lower. Based on the SNWTP data in Table 2, a limit of 109 million m^3/month was placed on the SNWTP water from Yangtze River. In the last scenario, an annual average sustainable groundwater pumping limit for the NCP users is also introduced. A study has modeled the annual NCP groundwater recharge rate as 17.77 km^3/year (Liu et al. 2011), which is scaled to the share of the Ziya River basin of the NCP (3.43 km^3/year) and distributed evenly to obtain a monthly limit. This groundwater pumping limit causes the users with the lowest curtailment costs (the farmers) to be curtailed and increases the water value to $2\text{–}2.5\text{CNY}/\text{m}^3$.

Simulating Water Allocation

The expected equilibrium water values were used to drive a 51-year reservoir operation simulation phase. From a starting volume at a given stage with known reservoir state and inflow class, the corresponding water value vector (all possible states in $t + 1$) represents benefits of storing water for future use in a forward moving optimization algorithm. The resulting reservoir management and perfect foresight DP solutions are shown for the three scenarios in Fig. 7. In general, the SDP simulations show the same trends as the DP solution, but the apparent interannual cycles primarily after 1980 are not captured by the SDP simulation. The DP solution will save water for these sequences of dry years, whereas the simple Markov chain runoff serial correlation will contain the same probabilities for each year. Therefore, the SDP solution releases more water in the beginning of the dry years and ends up with lower storage than the DP solution. Introducing a groundwater pumping limit (Fig. 7) will make the reservoir management more conservative because higher water values cause more water to be stored for the highest value water uses. Additionally, there is higher storage in the SDP solution than the DP solution. In Figs. 7 (a and c), the SDP solution shows higher reservoir states relative to the DP solution. This is caused by nonzero transition probabilities to a low inflow state; therefore, the SDP model saves water rather than curtailing expensive users.

The constraints can be modified to enable the evaluation of a variety of case setups and policy scenarios. Table 3 shows the total costs with SDP and DP for 12 different scenarios. From the difference in total costs between the scenarios, it is possible to calculate the average shadow price of water allocated to ecosystems (ecosystem flow constraint, as indicated in Table 2) or the SNWTP water. The SDs of the results have been calculated from the Monte Carlo simulations. The water diverted from the Yangtze River along the SNWTP middle route will lower the total costs with an average of $4.6\text{CNY}/\text{m}^3$ ($\text{SD} = 1.3\text{CNY}/\text{m}^3$). Forcing a minimum ecosystem flow of 100million m^3 to fill up the Baiyangdian Lake in July will, on average, cost $0.41\text{CNY}/\text{m}^3$ ($\text{SD} = 0.13\text{CNY}/\text{m}^3$) if the current practice continues with unlimited groundwater pumping. This indicates that the water allocated to Baiyangdian Lake will be substituted with groundwater pumping, which is available at a fixed cost of $0.4\text{CNY}/\text{m}^3$. If an average groundwater pumping limit is introduced, the average shadow price of the ecosystem water will be $2.78\text{CNY}/\text{m}^3$ ($\text{SD} = 1.04\text{CNY}/\text{m}^3$), indicating that the diversion will cause curtailment of the farmers. The differences between the objective values of SDP and perfect foresight DP are between 0.3 and 4.7% (average 1.8%) for scenarios without a groundwater

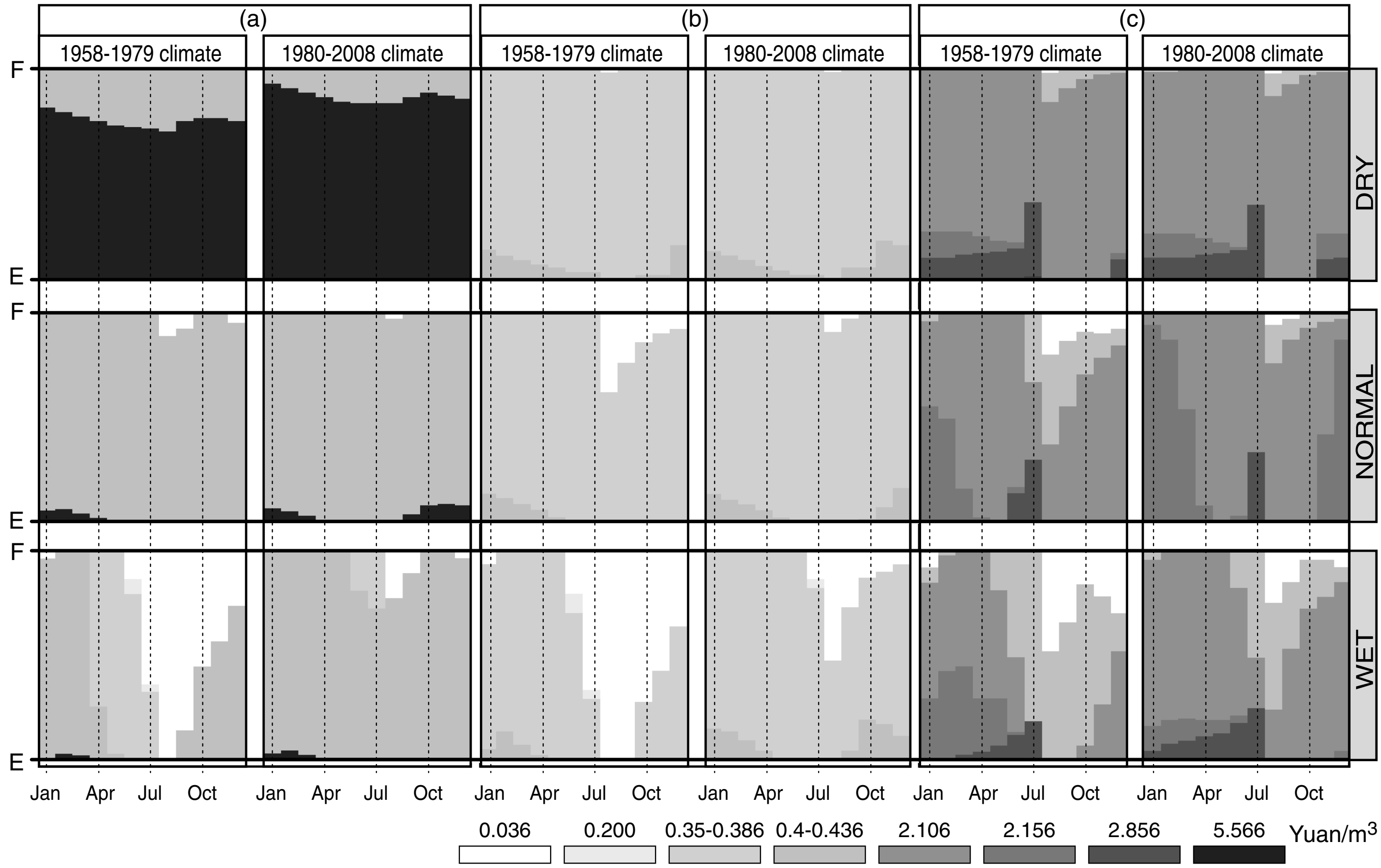

Fig. 6. Equilibrium water value tables for three different case setups, three different inflow classes (dry, normal, and wet) and two climate periods (before and after the climate shift in 1980): (a) setup with partly completed SNWTP (from Ziya basin to Beijing) and with unlimited groundwater pumping; (b) setup with finished SNWTP and unlimited groundwater pumping; (c) setup with finished SNWTP and a groundwater pumping limited to the average monthly groundwater recharge (y-axes represent reservoir storage: E = empty, F = full)

limit and between 3.6 and 5.7% (average 4.3%) for scenarios with a groundwater limit.

The impact of describing the runoff serial correlation can be found by comparing with a model run based on average monthly runoff from the 51 years. For the three scenarios presented in Figs. 6 and 7, the total objective values with runoff serial correlation were 3.70 billion CNY/year (SD = 0.6 billion CNY/year), 3.09 billion CNY/year (SD = 0.5 billion CNY/year), and 11.39 billion CNY/year (SD = 3.7 billion CNY/year), as listed in Table 3. Using average monthly flows instead, these total costs become 3.70, 3.21, and 12.02 billion CNY/year. The total costs with perfect foresight of 3.53, 3.06, and 10.75 billion CNY/year for these scenarios indicate the direct gain of using the stochastic representation of the runoff. The tradeoff for the higher accuracy of the SDP model is a computation time three times longer (66 s) than the model based on average flows (23 s).

Discussion

The purpose of this study is to demonstrate the potential use of SDP and the water value method in integrated water resources management for a complex management problem. It was found that the method can be used to assess the economic impact of changes in the hydraulic infrastructure and water policies. The SNWTP greatly changes the optimal management of the basin; the intermediate emergency diversion to Beijing (2008–2014) increases the water value, which implies more conservative reservoir storage, forcing more users to switch to groundwater pumping. Once completed, the middle route of the SNWTP will bring more water to the basin and reduce the total costs with 4.6 CNY/m^3 (SD = 1.3 CNY/m^3). This is approximately half of a World Wildlife Fund estimate of 9.3 CNY/m^3 for SNWTP water delivered to the Hebei Province (Berkoff 2003). Therefore, the shadow prices of the SNWTP water supplied to the users indicate that the SNWTP is not sufficient to balance a necessary reduction in groundwater pumping. Introducing a monthly groundwater pumping limit greatly increases the water values as the lowest value users are curtailed. Even when fully operational, the middle route of the SNWTP will not provide enough water (at least in the current setup) to avoid water curtailments of some users once the groundwater pumping limit is introduced. This aligns with the findings of Ma et al. (2006); therefore, the model results suggest that a sustainable groundwater abstraction can only be reached in combination with initiatives such as water recycling, efficiency improvements, pricing policies, and increased transfer capacity. The optimal reservoir management is greatly impacted by the limited groundwater pumping, and a new annual pattern occurs with steadier water levels in the reservoir until a rapid release in a single month. With increased water scarcity, the economic consequence of a wrong decisions increases, which is reflected in larger differences between the SDP model and the DP model.

It was found that SDP is a suitable and efficient method to determine optimal water management. The total costs found with

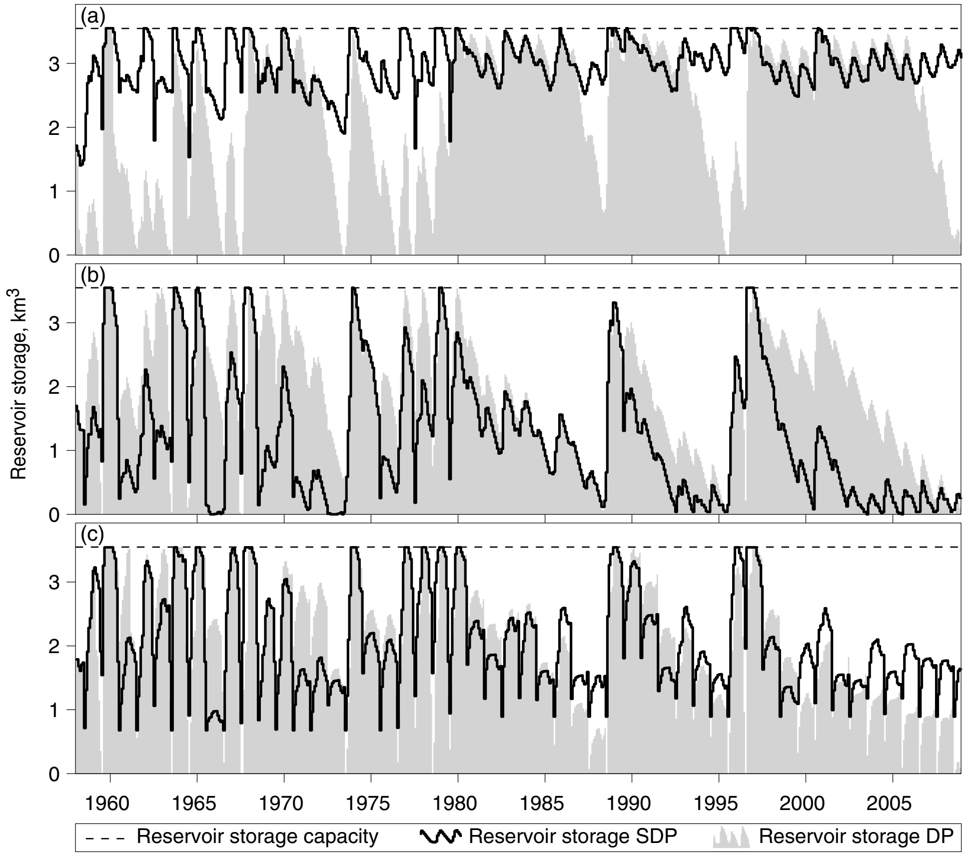

Fig. 7. Simulated reservoir storage using the SDP equilibrium water value table as rule curve, along with the perfect foresight DP solution for the three different scenarios: (a) setup with partly completed SNWTP (from Ziya basin to Beijing) and with unlimited groundwater pumping; (b) setup with finished SNWTP and unlimited groundwater pumping; (c) setup with finished SNWTP and groundwater pumping limited to the average monthly groundwater recharge

the SDP model lie within a few percentages of the total costs of a situation with perfect foresight, so the SDP model can be a valuable tool for decision makers. However, limits on the number of surface water reservoirs force the aggregation of multiple reservoirs to avoid high dimensionality of the optimization problem (Pereira et al. 1998) and imply some highly simplifying assumptions about the hydraulic infrastructure. Also, the simple Markov chain runoff serial correlation can be extended to capture the interannual wet–dry cycles, which seems to be present in the runoff time series. An example could be the hidden-state Markov chain, as applied by Fisher et al. (2012). This may make reservoir management more conservative in the years following a wet year, thus bringing the SDP solution even closer to the DP solution. With a single reservoir setup, the present model is also limited to a simple representation of groundwater pumping. Ideally, the groundwater should be included as another reservoir to assess actual impacts of management changes on the long-term groundwater table. This would also make it possible to introduce head-dependent groundwater pumping costs, which would make the objective function nonlinear. With such a scheme, it would be possible to analyze how different electricity prices affect the long-term groundwater table. The current single-step optimization problems were solved with linear programming. Linearity is not strictly necessary and nonlinearities may be accommodated, but with the potential limitation of increased simulation time. Howitt et al. (2002) demonstrated a solution to nonlinear optimization problems with general algebraic modeling system (GAMS), but other nonlinear solvers such as linear, interactive and general optimizer (LINGO) or genetic algorithms may be used.

Time linked constraints, such as fixing the long-term groundwater table or allowing the model to select the optimal timing of ecosystem water diversions, will introduce even more dimensions to the optimization problem. An alternative method such as stochastic dual dynamic programming, or SDDP (Pereira and Pinto 1991), may be a better choice for this type of complex problem. However, SDDP will only provide one solution (the optimal) with the given initial conditions. The SDP framework outputs the complete solution (water value tables), which can be used for adaptive management. Moreover, the simulation may use a more complex representation of the system, such as multiple reservoirs and more users. The intertemporal tradeoffs are determined from water value tables found in the optimization phase by using a simpler system representation. The computation time of the forward moving simulation phase is currently less than one second, so higher complexity can be accommodated. The optimization phase is also relatively fast; it would be computationally feasible to add another reservoir. Because the primary focus of this study is the upstream–downstream conflicts, all upstream users are aggregated and have access to the aggregated runoff. Thus, the Markov chain is based on the aggregated runoff. If the upstream basin is spatially disaggregated or if a second surface water reservoir is introduced, the number of possible inflow states will be increased. If the data were available, an alternative improvement would be to represent the users with demand curves. These could be implemented in the SDP framework, but would result in nonlinear one step ahead optimization problems. Thus, a nonlinear global solver such as genetic algorithms is required. To keep the one-step ahead optimization

Table 3. Average Annual Benefits and Costs with SDP and Perfect Foresight Benchmarks for 12 Different Scenarios

SNWTP status	E	GW	SP SNWTP	SD	SP E	SD	B_{hp} SDP	SD	TC SDP	SD	B_{hp} DP	TC DP
			CNY/m³	CNY/m³	CNY/m³	CNY/m³	Million CNY/year	Million CNY/year	Gross CNY/year	Gross CNY/year	Million CNY/year	Gross CNY/year
Pre-2008			—	—	—	—	74	41	8.69	1.9	72	8.66
Pre-2008	+		—	—	0.34	0.07	74	41	8.72	1.9	74	8.69
Pre-2008		+	—	—	—	—	86	40	17.01	4.2	89	16.40
Pre-2008	+	+	—	—	2.57	0.72	86	39	17.30	4.2	89	16.61
2008–2014			—	—	—	—	81	39	3.62	0.5	82	3.49
2008–2014[a]	+		—		0.60	0.25	81	39	3.70	0.6	82	3.53
2008–2014		+	—	—	—	—	87	40	13.60	3.9	89	13.06
2008–2014	+	+	—	—	3.26	1.77	87	40	13.78	3.9	88	13.31
Post-2014			−4.5	1.3	—	—	70	41	3.06	0.5	69	3.02
Post-2014[a]	+		−4.5	1.3	0.30	0.06	71	41	3.09	0.5	70	3.06
Post-2014		+	−4.7	1.2	—	—	86	40	11.12	3.7	88	10.54
Post-2014[a]	+	+	−4.7	1.2	2.50	0.63	86	39	11.39	3.7	88	10.75

Note: The shadow prices (SPs) of water to ecosystems and water from the middle route of the SNWTP are indicated. B_{hp} = benefits from hydropower production; E = minimum ecosystem flow constraint (to Baiyangdian Lake); GW = upper groundwater pumping constraint for the NCP users; post-2014 = SNWTP finished (water from Yangtze to Beijing); pre-2008 = before the SNWTP; TC = total costs; 2008–2014 = SNWTP partly finished (emergency plan); + = constraint active.

[a]These scenarios are presented in Figs. 6 and 7.

problem linear, the demand curves would have to be approximated by segments of constant curtailment costs and demands. This would increase the number of decision variables but would probably still be computationally feasible for a low number of segments per user.

Lack of public available hydrological, economic, and management data is also a great challenge when executing a case study in China. Despite multiple field trips and extensive online and onsite research, many rough assumptions were needed. Realistic curtailment costs are essential for the model to output realistic estimates, but even more important is the relative size of curtailment costs between the users, because this will determine which users to curtail and which to supply. Additional data on the producer prices, costs, and water demands for farmers and industries would reduce uncertainty of the curtailment costs and demand estimates. The SDs of the total costs are currently between 15 and 33%, and thus in the same range as the input uncertainty. This indicates that reduced uncertainty of the input data would lead to a proportional decrease in model output uncertainty.

The natural runoff was estimated with a simple hydrological model. The model was calibrated to a seminatural subcatchment and applied to the entire upstream area. It is not critical to assume the same calibration parameters across the catchments because the topography and vegetation across catchments are very homogeneous. The uncertainty of the hydrological model was not evaluated, because the primary focus of this study is to demonstrate the hydroeconomic optimization and simulation framework. It is expected that decision makers in China will have access to better calibration data, or ideally, measured natural runoff.

The results show the potential economic benefits if the system is managed according to the optimal solution. The results based on the best available data suggest that it is not possible to achieve sustainable use of the water resources without curtailing some users. The model can be used to identify the tradeoffs between the users and, ideally, which supplied users should compensate the curtailed users. However, the actual implementation of these compensation payments is an unresolved issue and outside the scope of this paper.

Conclusion

The water value method, a variant of SDP, was found to be a suitable approach for solving complex single reservoir river basin management problems. The optimization problem was defined as a minimization of water supply costs subject to a water demand fulfillment constraint. The resulting water value tables are efficient and illustrative tools to guide the decision makers; they can help to obtain a better quantitative understanding of the conflicts arising from water scarcity. Optimization run times are short and allow efficient analysis of multiple scenarios.

The optimization model can explain the consistent groundwater table decline that has been observed in the Ziya River basin. In the optimal solution, the water users of the basin will keep pumping groundwater until their demands are fulfilled, unless groundwater access is restricted. Without regulation, groundwater drawdown is expected to continue until the pumping costs exceed the curtailment costs of the users. The scenario results show that the middle route of the SNWTP will reduce water scarcity and impact optimal water resources management in the basin. The best available data indicate that the SNWTP will be insufficient to entirely avoid overpumping the groundwater aquifer, because introduction of average sustainable groundwater pumping limits greatly increased water values and caused curtailment of several users. Therefore, drier climate and high water demands remain unresolved challenges in the area.

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